Assessment and Characterization of the TWA Flight 800 Accident in Support of the National Transportation Safety Board

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Proposal for Assessment and Characterization of the TWA Flight 800 Accident in Support of the National Transportation Safety Board

Executive Summary

On July 17, 1996, TransWorld Airlines Flight 800, a Boeing 747-100, suffered major structural failures in mid-air off the coast of New York. Since that time, many competent federal agencies and their support organizations have conducted an extensive forensics investigation of the accident. The trail of evidence has pointed away from a terrorist act. It has become reasonably certain that the event did not result from a malevolent act; therefore, the investigation is refocusing to discover the cause of the accident. The purpose of this proposal is to detail the activities which Sandia National Laboratories (SNL) will perform to provide the National Transportation Safety Board (NTSB) with information to identify the location of the initiating event; the probable source of the initiation energy, and the basis for the NTSB to make recommendations to reduce the likelihood of such an accident in the future. This proposal includes integrated activities in systems analysis to identify single point failure modes and focus the investigation, in concert with modeling and analysis validated by testing, to provide an understanding of the combustion parameters, initiation sources, and structural response of the airframe.

Following is a brief outline of the scope of work that SNL proposes to support the NTSB's investigation of this accident.

- Review existing information with involved agencies/entities ;
- Develop systems analysis of active and passive systems affecting the safety of fuel tanks: Assess and characterize possible design failures;
- Identify potential sources of combustion initiation: Conduct electromagnetic analysis and testing to identify possible ignition sources;
- Investigate combustion conditions[1]
    - Analyze conditions in empty and partly empty fuel tanks
    - Compare the flame speed and overpressures between the simulant fuel at ambient conditions of the quarter-scale test program and actual Jet A fuel at the flight conditions of TWA 800;
- Develop structural testing, modeling, and analysis to assess the possibility of determining the ignition source location within the center wing fuel tank;
- Develop the basis for the NTSB's recommendations for mitigation of high-consequence risk factors identified; and
- Document the investigation in the form of reports and briefings.

SNL recognizes the urgency of completing this investigation and will focus to assist the NTSB in closing out its short-term investigation and support their efforts to define long-term solutions.

[1] The first portion of this work is represented in a proposal, *Proposed Joint Testing Program With Caltech: Large-Scale Testing of Fuel Tank Explosions*, submitted by SNL to the NTSB on June 4, 1997. It is included in Appendix D.

Introduction

Sandia National Laboratories (SNL) is a multi-program research and development laboratory operated for the US Department of Energy by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation. As a Federally Funded Research and Development Center, SNL carefully guards its ability to give respected, technically sound, objective assistance and advice. SNL avoids giving any party, including Lockheed Martin, an unfair competitive advantage. Pursuant to the prime contract between Sandia Corporation and the Department of Energy, SNL has developed and implemented an extensive program designed to avoid and mitigate such organizational conflict of interest (OCI) issues. SNL has submitted and obtained Department of Energy approval of its comprehensive OCI Management Plan.

Sandia is one of the nation's largest research and development facilities. It employs nearly 7600 people, about 60 percent of whom are in technical and scientific positions, with the remainder in crafts, skilled labor, and administrative classifications.

Its primary mission is the cradle-to-grave certification of the nuclear weapons stockpile for the national defense, with derivative missions in energy, the environment, and support of other federal agencies. As a result of developing tools to support the primary mission, Sandia has state-of-the-art equipment for computation (the world's fastest [massively parallel, teraflop] computer), environmental testing, radiation research, combustion research, and microelectronics research and production. Other major facilities include a new Explosives Component Facility; an Aerosol/Explosives Test Facility; the Airworthiness Assurance Nondestructive Inspection Center (AANC); a full-service Technical Library; a Primary Standards Laboratory; transonic, supersonic, and hypersonic wind tunnels; and design, fabrication, and process development laboratories. The investigation of the TWA Flight 800 accident of July 17, 1996, is the type of activity which may require such capabilities.

Traditional activities for SNL include the research and development of explosive technology and components. These activities involve the engineering of explosive, pyrotechnic, and propellant devices including detonators, detonation systems, deflagration-detonation transition devices, gas generators, igniters, rocket motors, and firesets. Activities dealing with experimental and analytical studies related to initiation, ignition, and detonation phenomenology, together with the development and application of computer codes and models for analysis and design, are also part of the overall explosives activities.

In addition, SNL is charged with designing systems such that the consequences of incidents and accidents, whether unintended mishaps or malevolent acts, involving transportation, handling, or storage of nuclear weapons, do not result in a nuclear detonation or a radiological dispersal. SNL must understand the threat environment, the system capabilities and vulnerabilities, physical protection, and mitigation technologies and strategies. In the event that an accident or incident does occur, these capabilities are also called upon to respond to the emergency, to diagnose the cause of any failures, and to recommend design or retrofit measures to significantly reduce the likelihood of a subsequent high-consequence occurrence.

A significant effort is also devoted to the study of materials behavior and performance as affected by exposure to normal and abnormal environments, together with the assessment of aging and compatibility effects.

As is true with TWA 800, the problems with which Sandia routinely deals are *systems problems* and must be viewed in a systems context. This necessitates the development of an integrated view of the role of activities that include testing, modeling, laboratory and field experimentation, and analyses – all of which must be focused on the achievement of specific objectives.

The combination of extensive investigative capabilities and the systems approach to problem solving have also led SNL to be involved in the resolution of other high-consequence mishaps such as the investigation of the explosion of the gun turret of the USS Iowa.[2,3] The systems approach is an area in which Sandia excels, and the type of overlying, integrating activity that characterizes much of our weapons work is included in this proposal.

Work Scope Activities

1. Review, as guided by the NTSB, existing information with involved agencies/entities including, but not limited to, the National Transportation Safety Board (NTSB); the Federal Aviation Administration (FAA); Boeing; TransWorld Airlines (TWA); the Federal Bureau of Investigation (FBI); the Central Intelligence Agency (CIA); and the Assistant Secretary of Defense/Special Operations Low Intensity Conflict (ASD/SOLIC)

Since the accident on July 17, 1996, a great deal of effort and expense has been incurred to understand the cause of the accident of TWA Flight 800. SNL believes that a significant amount of useful information is already available and could be used to limit the amount of new data that must be generated or collected. However, there are still gaps and unanswered questions that materially affect the ultimate outcome of the ongoing investigations. Before addressing these issues, however, SNL first proposes to thoroughly review existing information identified by the NTSB in the context of a systems framework to define an appropriate starting point for the investigations proposed here.[4]

[2] On April 19, 1989, the center gun room of Turret 2 of the USS Iowa exploded, killing 47 crewmen. Sandia was asked by the GAO to review the investigative work of the US Navy and subsequently to conduct supplemental experimentation and analysis to assist the Navy in resolving issues surrounding this incident. The final report is available in the GAO report GAO/NSIAD-91-45.

[3] Since 1950, there have been 32 accidents involving US nuclear weapons during transportation and storage. While the reports of these activities are classified, the issues surrounding some of the accidents are similar to those surrounding the accident of Flight 800.

[4] Any information received through these sources would be handled within strict non-disclosure agreements, or as classified information, as appropriate, and protected under well-established document control programs.

For example, it is likely that coordination with Boeing in the preparation of structural models will significantly reduce the time and cost of preparing the necessary finite element models. Similarly, much of the system fault tree analysis may already have been done during the original certification process. In that case, a review of the information may be all that is necessary to better understand the issues surrounding the systems affecting conditions within the fuel tank and may direct the nature of the electrostatic testing to be performed. Interaction with knowledgeable people from the various agencies and entities who have been involved is also important from the perspective of gaining additional insight into events surrounding the accident.

The agencies listed above are those of which SNL is aware that may have contributed in some way during the investigation to date. SNL would look to the NTSB for guidance about the appropriate interactions and the appropriate agencies/entities.

2. Systems analysis of active and passive systems affecting the safety of fuel tanks: assessment and characterization of possible design failures

Fault tree and/or event tree analysis of various systems and subsystems may have been performed as part of the normal certification process. If these documents are available, SNL would propose to review this information, perhaps extending it in some areas, as appropriate.

The independent assessment of the design and safe performance of nuclear weapons under all accident conditions has led Sandia to a unique perspective to assuring the safe performance of high-consequence operations. High-consequence designs and operations, by their very nature, must be extremely safe -- the consequences of accidents are intolerable to the public. Sandia uses a combination of fundamental principles of design and powerful engineering analysis tools to assure the safety of our systems through proper design without reliance on the low probability of the accident. This combination also provides a unique and powerful perspective for accident investigations. Not only can we understand what may have caused accidents to occur, but we also can point to fundamental improvements that could significantly reduce the possibility of such accidents in the future. These improvements may either eliminate the fundamental causes of the accident or render the outcomes of these causes to be inconsequential. We propose to apply these approaches to assist in understanding the TWA 800 accident and to formulate recommendations for assuring that the probability of similar accidents is significantly reduced. The essence of the approach is as follows:

2.1 Identify the safety theme[5]

To identify the safety requirements for the design and to identify those essential elements of the design, their underlying principles, and the interrelationships which are relied upon to assure safety, SNL will identify the safety *requirements* of the system; we refer to this as the *safety theme.* This will identify those key aspects of the design for which configuration control, surveillance, and inspection are essential to ensure the continued integrity of the design.

[5] See Appendix A for a discussion of Sandia's approach to system safety.

2.2 Develop potential failure modes and scenarios consistent with the failures observed and the identified safety theme

A good deal of work has already been done by the NTSB and others in the area of identifying potential failure modes and scenarios. SNL will review all available information, and use it to describe and set forth in a systematic, theme-based, and independent fashion, the possible ways in which the design might have failed, leading to the observed consequences. During this review, SNL will examine the design of the fuel system and other relevant systems to verify all credible potential failure modes and scenarios, the consequences of which could have been those that were observed. This will be done using both principle-based and model-based techniques, as described in Appendix A.

2.3 Build an integrating framework for the investigation

To provide an analytical framework for examining parameter variations, sensitivities, and uncertainties, SNL will build a logic model which would tie together the various portions of the analysis, providing an integrating framework and an analysis framework for examining parameter variations, sensitivities, and uncertainties. The pieces to be integrated are as follows:

- Sources of initiation coupled with fault tree analysis investigations (Sections 2.2 and 3);
- Combustion conditions – fire/flame propagation and resultant overpressure conditions on the structure (Section 4); and
- Structural response – response of the airframe (Section 5)

The model will also provide a means of understanding the relationship of the various detailed analyses to overall system performance and response to adverse conditions.

2.4 Integrate forensic, analytic, and experimental data

To maintain the focus of the evaluation upon those scenarios which are consistent with the available evidence, SNL will continually examine the existing forensic, model-based, and experimental evidence and couple it to the identified failure modes and scenarios to focus the evolving evaluation on those scenarios which are consistent with the evidence. Statistical design of experiments will be used to assure that information gained is relevant, accurate, and statistically significant. Experimental and modeling refinement will continue as additional understanding is obtained which could provide further insight into the cause of failure.

2.5 Provide the basis for NTSB's recommendations for future avoidance of similar failures or accidents

To provide an integrated systems understanding of the fuel system, a basis for the NTSB's recommendations, and a means to evaluate possible options that significantly reduce the probability of failure in the future, SNL will categorize possible failures in terms of engineering design principles and safety themes.

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3. Sources of Combustion Initiation: Electromagnetic analysis and testing to identify possible ignition sources

The proposed research and test program should address generic problems first and should then address each failure scenario, in order from most probable to least probable. Much of the testing should be conducted on a Boeing 747 of the same vintage, preferably the same specific model and a close serial number.

3.1 Development of failure scenarios

An inspection of the Faraday cage formed by the center wing fuel tank and the penetrations and bonding of the metallic penetrations into the center wing fuel tank suggested a number of electrical failure scenarios that should be examined in detail to ascertain their likelihood of causing the accident. Given the absence of the intact system, and the likely differences between the vehicle involved in the accident and any aircraft that may be used for testing, the most likely outcome of the investigation is that the probable cause of the initiating event could be limited to a relatively small number of possibilities.[6] Correlation between this information and the structural analysis and testing could further limit the number of plausible scenarios.

3.2 Fuel/air mixture fast-rise-time spark initiation study

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A critical input required to assess any of the spark initiation scenarios is the minimum spark energy required to initiate flammable fuel/air mixtures. This testing will be coordinated with the parametric combustion testing and analysis. Testing of solid explosive materials has shown that initiation threshold energies may vary five orders of magnitude (from greater than 64 joules to less than 20 millijoules) depending on the rise time of the current applied to the sample. Electrostatic discharges characteristically have the shorter rise times. The more realistic a simulation of electrostatic discharge is (i.e., the shorter the rise time), the less energy required to initiate the explosive. Similar studies have not been performed on fuel/air mixtures, but such testing could potentially demonstrate that the minimum energies required for initiation are significantly below the 0.2 millijoules quoted in the literature and used for the accident assessments to date. Because the rise time of the current changes the amount of electrical energy that ends up as heat, shock, optical, and chemical energy, it is not unreasonable to expect that the thresholds would change depending on the rise time. Depending upon the minimum spark initiation energy, some scenarios are much more plausible than others. Therefore, SNL proposes to determine a series of minimum energy thresholds for various fuel/air mixtures at various pressures using SNL's unique cable discharge system and associated high-bandwidth instrumentation and probe. The thresholds determined with sub-nanosecond rise time current pulses may drive the direction of the investigation.

3.3 Fuel-level sensor wiring breakdown testing

If electrostatic discharge or another high voltage transient of several thousand volts is conducted to, or induced on, wiring to one or more fuel-level sensors, breakdown could

[6] For possible event initiation scenarios, see Appendix B.

occur through insulation between exposed wires that go to the fuel-level sensor. Alternatively, breakdown could occur at the wiring bulkhead connection inside the tank. Either condition could initiate the fuel/air mixture. SNL proposes to investigate the likelihood of this scenario by determining: the static voltage standoff and likely location of the fuel-level sensor wiring arc given a high voltage applied to the wiring outside the center fuel tank; the fast-rise-time, high voltage pulse transient coupling from wiring outside the fuel tank to inside the fuel tank; and the plausibility of electrical system failures resulting in a voltage surge to the fuel-level sensor wiring.

3.4 Low frequency current division testing

If the hot bonding strap were to partially fail from vibration or other damage, leaving a few strands of a bond strap connected, the bonding strap could become a potential ignition source. To understand the likelihood of such an event, SNL would determine the current thresholds for bonding strap strands to reach fuel/air mixture temperature flammability thresholds, using Fluoroptic thermometry techniques to measure temperature and thermal time constants of heating/cooling directly; measure low frequency current division by applying a current source to metallic penetrations outside the center fuel tank and measuring where current distributes inside the fuel tank; and measure resistances of various bulkhead connections, straps, and electrical connections to construct a rudimentary resistive model and to ascertain uncertainties in the resistances; and determine the likelihood of ground fault or multipoint ground existing in the aircraft electrical power system which could result in the current necessary to initiate a combustion event.

3.5 Electrostatic discharge inside-tank testing

In the event that a bonding failure occurs through vibration or other damage and electrically isolates an exposed piece of piping or other metal inside the center wing fuel tank, fuel motion pumping or spraying could generate a charge on the isolated metal. A spark discharge occurring between the isolated metal and any metal piece bonded to the fuel tank could ignite the air/fuel mix. To understand this potential failure, SNL would determine: the voltage standoff provided by a single point failure of bonding in Wiggins couplers, bond strap failure, corroded bulkhead connectors, and other standoffs, as necessary; the charge generated by pumping/spraying/sloshing; capacitances of isolated metal structures produced by bonding failures; voltages generated by the charge and associated capacitances; and the possibility of initiation of the fuel/air mixture by a spark produced by such a mechanism compared with the minimum initiation energies determined in 3.2, above.

3.6 Fast-rise-time transient testing

Should corrosion or oxidation occur between a metallic penetration and a bulkhead connection, it could cause a large dielectric isolation of a few kilovolts or more. A fast current surge from failed electrical equipment could then flow through the fuel-transfer, fuel-delivery, or fuel-vapor-venting piping penetration into the fuel tank. Inductance of the bonding straps, times the rate of rise of the surge current, would yield a voltage large enough for breakdown to occur between metal piping attached to the bonding straps and the fuel tank, thereby initiating the fuel/air mixture. To investigate this possibility, SNL proposes to determine: the maximum breakdown voltage provided by corroded bulkhead connections; the rate-of-rise of current required to generate breakdown voltage; conducted high-voltage, fast-rise-time transient into the tank through the metallic penetrations; and the possibility of initiation by this mechanism.

4. Combustion Conditions

Have Merritt check CMR + Los Alamos re. their code. Oak Ridge

4.1 Analyze conditions in empty and partly empty fuel tanks

CONTAIN, a modeling and simulation tool developed by SNL, is the US Nuclear Regulatory Commission's leading simulation tool for containment analysis. It provides an integrated treatment of fluid flow, heat transfer, combustion, and aerosol behavior in complex interconnected volumes. Developed over the past 15 years, it enjoys widespread US and international use. The CONTAIN validation database includes detailed comparisons to some 70 different experiments, including ones with highly stratified conditions. As a result of extensive code development and validation, the CONTAIN code is able to predict the behavior of experiments with significant vapor stratification, a process that may be of significance in the fuel tanks of TWA 800.

Recently, CONTAIN has successfully supported a multi-disciplinary team analyzing non-reactor problems such as the assessment of accidental non-nuclear explosions in weapons assembly rooms at the Pantex weapons assembly plant; and the response of B-52 aircraft wing tanks to external fuel fires. Modifications of CONTAIN to include JP-8 fuel properties was accomplished for this study and will be needed for the TWA 800 accident analysis.

In the evaluation of the TWA 800 accident, SNL proposes to use CONTAIN to provide detailed evaluation of conditions in empty and partly empty fuel tanks. Because CONTAIN is fast-running, numerous scenarios can be readily simulated, thus providing a quick assessment of the credibility and importance of postulated events. The code can account for buoyancy driven flows and allow fuel sloshing to be approximated. The code can also account for mixing between cells to determine the local fuel to air ratio and the possibility of ignition. The potential for combustibility and detonability can be explored based on specified fuel management actions

CONTAIN will be used both to analyze the experiments simulating conditions in the fuel tank and to evaluate the in-flight initial conditions used in the deflagration and loads analyses to be performed with other codes. Early analysis of the available experiments is proposed to allow rapid feedback with respect to adequacy of the experimental instrumentation and conditions to be incorporated in subsequent experiments. Later analyses will be more refined to evaluate uncertainties in the initial conditions. This will be important in providing recommendations of a reasonable number of scenarios to be fully evaluated with respect to deflagrations and loads. The CONTAIN evaluation may include use of the CONTAIN internal deflagration models to determine the merits of potential scenarios to be analyzed further.

Uncertainty in the vapor-air stratification in the tank affects the determination of flammability and propagation of burns in the tank. In the absence of strong mixing forces, it is unlikely that idealized well-mixed conditions are applicable. In extreme cases the average vapor-air mixture in the compartment may be flammable, but the local mixture at the postulated ignition point may be nonflammable. (Ignition sources for use by the CONTAIN code will be determined through the analysis and testing conducted in Sections 4 and 5 of this proposal.) In less severe cases the mixing process may be strongly coupled to flow turbulence, a circumstance that significantly complicates the analysis of burn propagation. Thus, another important role of CONTAIN will be to evaluate the degree to which the tank is stratified.

4.2 Compare the flame speed and overpressures between the simulant fuel at ambient conditions of the quarter scale test program and actual Jet A fuel at the flight conditions of TWA 800

The parameter sensitivity study currently planned at one-quarter scale will use a gaseous fuel to simulate the Jet A vapors resident in the center wing fuel tank during take-off and ascent of TWA 800. A simulant is necessary because the temperature and pressure used in these studies will be different from that which existed in the aircraft at altitude.

The proposed follow-on work will provide experimental data comparing the flame-acceleration potential and overpressures of the Jet A simulant to that of Jet A. The goal of this follow-on work will be to determine whether the simulant fuel adequately represents the actual fuel. The work is directly complementary to the laboratory-scale tests conducted at the California Institute of Technology (CIT, or Caltech) which studied the flammability limits of Jet A. Additionally, the proposed work complements the quarter-scale tests and the small-scale tests being proposed CIT. We propose to work closely with CIT during the quarter-scale test program[7] and during this proposed follow-on work.

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The work would be conducted in Sandia's Heated Detonation Tube (HDT) which is an enclosed vessel, 43 feet long (but could be shortened to 20) and has an inside diameter of 16 inches. Like the laboratory-scale facility at CIT, test can be conducted in the HDT reduced pressures, representing the effects of altitude, and at temperatures up to 100° C. Ignition will occur by spark (high voltage bridgewire ~ 4 joules), and the ignition location could be varied if desired. The HDT can also be fitted with baffles to represent the spars and spanwise beams in the tanks. Holes will be made in the baffles, permitting passage from region to region, similar to those in the center fuel tank. Finally, success of the program depends on careful measurements of initial vapor concentrations, defining the initial conditions for combustion. One of SNL's mass spectrometer could be modified to measure these vapor concentrations; coordination and comparison with the ongoing vapor measurement project will help bound any uncertainties in this approach.

[redacted]

[7] Sandia's proposal for support on the quarter-scale testing, *Proposed Joint Testing Program With Calthech: Large-Scale Testing of Fuel Tank Explosions*, was submitted by SNL to the NTSB on June 4, 1997. See Appendix D.

The proposed study will look at the damage potential of flammable mixtures from mixtures near the flammability limit to those that show clear flame acceleration potential. As with previous studies on low-molecular-weight gases, it is anticipated that Jet A will show the ability to create dynamic loads with only slight increases in concentration above the lower flammability limit.

If confirmed, this information would be useful in supporting the argument that exceeding the lower flammability limit represents entering a single-point failure regime in which easily achieved concentrations of ullage gasses can produce pressures which are impractical to design against.

Costs could be minimized for the proposed program if the quarter-scale testing program being proposed by CIT were performed at Sandia. For example, instrumentation and the data-acquisition system will be shared by both programs.

As with any one-of-a-kind project, there are limitations and risks. The geometry of the HDT is not exactly the same as the TWA 800 fuel tank. If anything, the HDT will accentuate the flame acceleration potential of the fuel compared to the actual fuel tank due to the close confinement of the walls compared to the tank. However, the resulting comparison between the simulant and actual jet fuel will provide confidence that the simulant was, or was not, adequately chosen.

5. Structural and combustion testing, modeling, and analysis to assess the possibility of determining the ignition source location within the center wing fuel tank

The structural and combustion testing, modeling, and analysis consists of five elements, as described below.

5.1 Inspect reconstructed airframe[8]

Investigate the nature of the damage to the reconstructed airframe in order to determine if it is possible to separate the pressure load from the structural breakup and water impact, and to determine whether the event in the center wing fuel tank had been a high pressure, rapid-rise-time event, or if the event was a slow burn that resulted in enough pressure to burst the tank. (A slow (1-2 second) pressure rise will make the inverse problem impossible to solve.) Results:

- *There is information from the explosion and decompression that can be separated from the breakup and water impact. Therefore, it is useful to continue to develop analysis models of the structure to correlate with the reconstructed airframe.*[8]
- *The observed deformation is not consistent with a static pressure buildup (slow pressure rise time).*[8]

[8] The first task has been essentially completed as part of a pre-proposal activity and is detailed in Appendix C.

5.2 Construct a detailed model of the center wing fuel tank with surrounding structure, based upon geometry models available from Boeing

In order to properly compare the structural analysis with the observed damage, a very detailed structural analysis will be required. The analysis must include the vertical stiffeners on the span wise beams and the spars. In addition, the stringers on the top and bottom panels of the wing center section will need to be modeled. Fixed contacts will be used to model the rivets between the stringers and stiffeners. Some code modification will be required to allow the fixed contacts to simulate the rivet failure and recontact. Failure will be modeled using a damage model. In the cases where more local failure will need to be modeled (bolt failure, rivet failure, some fractures, etc.), the equivalent failure stress must be determined.

In order to model the decompression, the ullage/air in the bays will be modeled using fluid-like elements. It will be necessary to construct a separate mesh to perform the fluid/combustion analysis (section 5.3, below). The results from this analysis will need to be mapped to the structural analysis model to perform the uncoupled calculation (section 5.4, below).

5.3 Model a pressure event in a single tank compartment using the maximum estimated rise time (from testing or from a combustion model)

To determine the loading conditions for the mechanics analysis, it is necessary to model the reactive fluid mechanics of the combustion event. A detailed first-principles analysis is beyond any known capability; however, an estimate of delivered impulse is of interest and resolving detailed reactive fluid mechanics may be unnecessary. Much simpler approaches can be used to provide structural loading conditions by simplifying the flame propagation. Experimental measurement of turbulent flame speeds can be adapted in the limit of low speed flow whereby pressure in each compartment becomes spatially uniform. Transient pressure drop between coupled cavities (or bays in the fuel tank) can be estimated using simple fluid mechanical models, similar to such estimations for reactor safety analysis.

In modeling this mode of combustion, the flame is treated as a moving discontinuity using flame sheet analysis. This method accommodates acceleration effects in coupled cavities using experimental measurement (or educated guesses) of flame speed. The overall flow field includes pressure losses and heat transfer between regions. Such an analysis exists and is easily modified to treat the reactive gases of interest. Although this type of analysis is not "back of the envelope", it can be used in parametric and sensitivity analysis. For example, changes in ignition location can be varied to yield overall impulse to each bay in the fuel tank.

At the other limit of modeling, one could also assume that the flow is highly turbulent and the run up to detonation is negligible. Models for gas phase detonation exist in such codes as CTH using chemical equilibrium analysis as input. As in the case of modeling accelerated flames, initial compositions and temperature are assumed which then can be modified with experimental measurements. A program CJ burn calculation can be done to yield a three-dimensional map of the dynamic pressure field. SNL has done this type of modeling in prior hazards studies with great success. Such three dimensional analysis is, however, computationally expensive, and fewer simulations can be done with this dynamic analysis. Both types of modeling (quasi-static and dynamic) provide bounds on the structural response. As in the case for flame-sheet accelerated propagation, dynamic analysis currently exists and is readily applicable for determining loading conditions.

5.4 Perform uncoupled calculation of the center wing fuel tank

Model the combustion process assuming the structure does not move. Scale model testing[9] will be used to validate the model of the pressure in each of the compartments.. Use this model to determine the pressure time histories in each of the compartments, assuming that the compartments do not fail. Use this pressure time history in a structural model to see if the model failure matches the observed mode of failure. Calculations will be performed with the Pronto/SPH code, where Smooth Particle Hydrodynamics (SPH) is used to model the pressure in the compartments, and traditional finite elements are used to model the deformation and failure of the wing tank structure. The calculations will be performed on the Intel massively parallel teraflop computer at Sandia National Laboratories. Another possible code for this calculation is ALEGRA, which employs Arbitrary Lagrangian Eulerian (ALE) solution methods.

Structural testing will be done to support the development of models to predict failure of structural components in the center wing fuel tank. Appropriate tests of compartment doors, structural tube assemblies, and joints will be subjected to simulated explosive loading to quantify failure limits for input to the structural response codes. The loads and associated structural deformation and failure from the test program will be compared with damage observed in the center wing fuel tank. This data will help quantify the sequencing of events which occurred during the accident and aid in identifying the initiation location.

The first phase of the structural testing will be to identify and secure the set of sub-structures to be tested. Potential tests are:

1. Vent and fuel tubes - external pressure tests to determine pressure loading histories and tube crush strength.

2. Span-wise beams and honeycomb access doors - simulate pressure loads to determine deformation histories and failure mode levels.

3. Keel beam - failure in bending

4. Tensile tests on fastener assemblies in span-wise beam

5.5 Construct and analyze a coupled combustion/structural model of the center wing fuel tank

If the uncoupled combustion and structural models do not match observed modes of deformation and failure, then the next step is to construct a fully coupled model. This model will require experimental validation from combustion testing and analysis (Section 4, above). These calculations are particularly sensitive to the initial conditions in the

[9] This testing will require 'exact' modeling of the surface features in the tank.

compartments of the center wing fuel tank, i.e., the temperature and fuel/air mixtures. This sensitivity makes it a longer, more difficult, modeling effort, and introduces uncertainties into the final results. Before initiating this task, SNL and NTSB must evaluate the confidence in prior analyses and tests to determine the utility of proceeding.

6. Develop documentation in the form of reports and briefings regarding the full scope of work performed, as well as any recommendations for mitigation of high-consequence risk factors identified

SNL will provide a detailed final report, with interim reports, as appropriate, for use by the NTSB. It will include a rigorous accounting of the experimental and analytical methods and assumptions used in performing the work. This report will be provided to the NTSB and those that they designate for their review and comment prior to final publication. Distribution of the information will be determined by the NTSB.

Proposed Schedule: Assessment and Characterization of the TWA Flight 800 Accident

Activity	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Cost ($K)
	1997 Q4			1998 Q1			1998 Q2			1998 Q3			
1. Review of existing materials	Start					End							330
2. Systems analysis of passive & active systems	Start											End	450
3. Sources of combustion initiation	Start							End?*					1100
4. Combustion conditions													
4.1 Analysis of conditions in empty and partly empty fuel tanks	Start											End	475
4.2 Fuel comparison testing	Start											End	1550
5. Stuctural and combustion testing, modeling, & analysis	Start							End					1120
6. Reports											Start	End	150
Totals													5175

* End of test is determined by the availability date of test hardware. *Cost does not include hardware acquisition.*

Appendix A: Sandia's Philosophy of System Safety

The independent assessment of the design and safe performance of nuclear weapons under accident conditions has led Sandia to a unique perspective to assuring the safe performance of high-consequence operations. High-consequence designs and operations, by their very nature, must be extremely safe -- the consequences of accidents are intolerable to the public. Sandia uses a combination of fundamental principles of design and powerful engineering analysis tools to assure the safety of our systems through proper design without reliance on the low probability of the accident. This combination also provides a unique and powerful perspective for accident investigations. Not only can we understand what may have caused accidents to occur, but we can also point to fundamental improvements that could significantly reduce the possibility of such accidents in the future. Design or process improvements may either improve the failure characteristics of the system, or change the likely consequences to ones which are less severe. Sandia proposes to apply these approaches to assist the NTSB in understanding the TWA 800 accident and to provide the basis for the NTSB's recommendations to reduce the probability of a recurrence.

The essence of our approach is as follows:

1. Identify the safety requirements for the design and identify those essential elements of the design, their underlying principles, and their interrelationships which are relied upon to assure safety; we refer to this as the "safety theme." Identify those key aspects of the design for which configuration control, surveillance, and inspection are essential to ensure the continued integrity of the design.

2. Evaluate the design and its performance under all conditions to understand the adequacy of the safety theme to assure safety. We do this through the application of fundamental design principles and engineering analysis tools which integrate component performance with physical processes to evaluate overall system performance. For accident investigations, we focus on the conditions present at the time of the accident.

3. Identify regimes in which the safety theme breaks down, identify potential failure modes, and construct accident scenarios which could result in an undesired event.

4. Develop recommendations for design safety improvements or, in the case of accidents, improvements which will reduce the probability of similar accidents in the future.

Sandia's approach is used in the design of nuclear weapon systems; moreover, these approaches have provided unique insight into high-consequence accidents, such as the USS Iowa turret explosion. The breadth of capabilities that are brought to bear, our combination of principle-based design and model-based analysis techniques, and our independent assessment perspective represent a unique combination of talents to meet the needs of the National Transportation Safety Board.

The first-principles approach

In classical high-consequence system safety, hazards are eliminated whenever possible, and control is exercised over the probability of the occurrence of events that can lead to undesired consequences from the remaining hazards. In nuclear weapon safety, the component and system designs that may result in nuclear detonation are virtually eliminated by the physical first-principle design approach. For each weapon, a *safety theme* is developed that describes how safety requirements are met in the design through coordinated application of a minimal number of safety-critical components and, in particular, how engineering design principles are to be implemented so that they can be depended upon through every phase of the use environment.

One important criterion is that implementation of the design should be based on fundamental physical and chemical understanding of the system properties such that safety is maintained or a fail-safe condition is rendered in all environments. In addition, specially controlled independent redundancies are used to ensure that numerical design goals are achieved, and fault trees are used to ensure that all failure modes are appropriately understood and compensated for.

The application of this approach to aircraft fuel system safety would involve consideration of the basic principles of mitigating against a fire or explosion. This would be done both in the investigative phase to determine whether, and to what extent, such principles had been implemented, and with what assurance that they were adequate, and then in the option development phase to find ways of further implementing the principles. The activity would begin by formulating principles of the following *type* for use in these ways. Using basic physical principles whenever possible:

1. Reduce/eliminate hazards: Reduce, as far as practical, the potential for flammable or explosive mixtures in the fuel system (e.g., through methods of controlling the fuel/oxygen ratio or temperature) through all phases of operation.

2. Isolate ignition sources: Reduce, as far as practical, the potential for undesired ignition sources in the fuel system (e.g., pumping, venting, level measurement systems) through all phases of operation.

3. Control ignition sources: Ensure, as far as practical, that existing potential ignition sources are inoperable in the presence of flammable or explosive fuel mixtures (e.g., through sensing) through all appropriate phases of operation.

Model-Based Assessment Techniques

Sandia performs systems analysis of high-consequence systems. One of the characteristics of the analyses of high-consequence systems performed at Sandia is the ability to construct a synthesizing logic structure to bring together information from a multitude of scientific and engineering disciplines in a systems engineering approach. Event trees and other logic tools are used for this integration task. The task is to bring together information about the probabilities of various events from fault trees, historical data, and the results of experiments and computer simulations. For the center fuel tank in a 747, for example, the information to be integrated might include the energy available from the various ignition sources and the probability that each ignition source could have provided a spark, the results of computer simulations of the fuel vapor – air mixture in the tank as a function of time, the output from flame propagation and pressure rise models, and computations of the fuel tank structural response to various pressure levels and pressure rise times. The event tree also serves to delineate the numerous possible scenarios, calculate their probabilities, and determine the uncertainties in those probabilities.

The use of an event tree in this synthesis role is not new. For more than two decades, event trees have been used for this purpose in probabilistic risk analyses of nuclear reactors. For example, in the analysis of a core meltdown accident, an event tree is used to integrate the probabilities that cooling pumps will fail and other events will occur together with experimental and model results concerning the increase of temperature and pressure in the reactor containment, the structural response, and the interaction of the molten core with the concrete floor.

Model-based assessment of high-consequence systems at Sandia began decades ago with analyses of nuclear weapons and reactor accidents and has expanded to include failures of robotics systems, transportation accidents, and terrorist attacks on high-value targets. The emphasis in all these analyses has been on comprehensive assessments with a thorough treatment of all the uncertainties involved.

The integration of physical response models, e.g., thermal and structural response calculations, into the probabilistic fault tree and event tree analysis has been a key development. Highly efficient search algorithms that utilize the model results allow specific abnormal conditions that might threaten the system of interest to be efficiently identified. Incorporation of the physical response models enables Sandia to perform a comprehensive, integrated analysis of complex, dynamic events such as aircraft crashes.

Summary

Sandia's principle-based design and model-based analysis techniques provide a unique systems approach to accident investigation. Sandia's combination of analysis, engineering, and test capabilities offers a powerful capability to support the National Transportation Safety Board in its investigation of the TWA 800 accident.

Appendix B: Potential Failure Initiation Scenarios Suggested by the Inspection of the Reconstructed Airframe

An inspection of the Faraday cage formed by the center fuel tank and the penetrations and bonding of the metallic penetrations into the center fuel tank suggested a number of electrical failure scenarios that should be examined in detail to ascertain their likelihood of causing the crash. Given the absence of the intact system, and the likely differences between the vehicle involved in the accident and any aircraft that may be used for testing, the most likely outcome of the investigation is that the probable cause of the initiating event could be limited to a relatively small number of possibilities. The electrical initiation scenarios that were identified by SNL and others are given below in a somewhat arbitrary assignment of likelihood of occurrence:

B1. Fuel-level sensor initiation

1. Electrostatic discharge or another high voltage transient of several thousand volts or more is conducted to or induced on wiring to one or more fuel-level sensors.
2. Breakdown occurs through insulation between exposed wires that go to the fuel-level sensor or inside the tank at the wiring bulkhead connection.
3. The fuel/air mixture is initiated.

B2. Hot bonding strap low frequency initiation

1. Bonding partially fails from vibration or damage, leaving a few strands of a bonding strap connected in the fuel transfer, fuel delivery, or fuel vapor venting piping.
2. A small amount of corrosion or anodization creates a preferential low resistance path through the strands of the strap. A higher resistance occurs through the bulkhead connection.
3. A ground fault or a multipoint ground in the airplane power system provides current of 1 to 100 amperes to heat the strands above the flammability temperature. If the strands are intact, probably a few thousand amperes would be required to heat the strap to the flammability temperature.
4. The fuel/air mixture is initiated.

B3. Bonding failure electrostatic discharge initiation

1. Bonding fails from vibration or damage and electrically isolates an exposed piece of piping or other metal inside the center wing fuel tank.
2. Fuel motion, pumping, or spraying generates a charge on the isolated metal.
3. A spark discharge occurs between the isolated metal and a metal piece bonded to the fuel tank or to the fuel tank itself.

4. The air/fuel mixture is initiated.

B4. Fast transient bonding failure initiation

1. Corrosion or oxidation causes a large dielectric isolation of a few kilovolts or more to occur between a metallic penetration and a bulkhead connection.
2. A fast current surge from failed electrical equipment flows through the fuel transfer, fuel delivery, or fuel-vapor-venting piping penetrating into the fuel tank.
3. Inductance of the bonding straps times the rate of rise of the surge current yields a voltage large enough for breakdown to occur between metal piping attached to the bonding straps and the fuel tank.
4. The fuel/air mixture is initiated.

B5. Fuel pump failure initiation

1. Massive structural failure of the fuel pump and its seal occurs.
2. Electrical connection is made between the fuel pump electrical system and the pump impeller.
3. An arc occurs between the impeller or its shaft and the pump housing.
4. The fuel/air mixture is initiated.

B6. Alternate Fuel Tank Initiation

1. Any of Scenarios B1 through B5 occurs in another fuel tank.
2. Flame propagates to the center fuel tank through fuel or venting plumbing.
3. The fuel/air mixture in the center fuel tank is initiated.

These scenarios, most of which have probably already been identified by the NTSB and Boeing, suggest a series of tests and experiments which should be conducted to quantify and qualify or dismiss them as potential causes of the accident. Scenario B5, *Fuel pump failure initiation*, is best addressed by direct testing of the pumps to failure and is being addressed directly by others. Consequently, this scenario will not be addressed by the proposed program.

Appendix C: Review of Reconstructed TWA Flight 800 Airframe

The NTSB has asked Sandia to assess the possibility of determining the ignition source location within the center wing fuel tank. The method suggested for this task was to solve the inverse problem by using the deformation of the center wing fuel tank to back out, or reverse calculate, the driving pressure. The driving pressure would then be combined with a model of the combustion process to determine the source of the explosion. Many potential sources of ignition exist within the fuel tanks, and simply determining if the source was in the front, back, or center would provide some pertinent information.

As an initial step in the analysis, on May 29, 1997, Sandia sent a team to visit the TWA 800 reconstruction site. The purpose of the visit was to determine whether the event in the center wing fuel tank was a high pressure, rapid-rise-time event, or a slow burn that resulted in enough pressure to burst the tank. A slow (1-2 second) pressure rise will make the inverse problem impossible to solve.

The Sandia team searched for any clues that would indicate any evidence of:

1. the pressure rise time,
2. the maximum pressure,
3. a non-uniform overpressure loading.

C1. Description of findings

The wing center section (WCS) is a large box-shaped section located between the wings. The WCS is bounded by the wing front spar (FS), wing rear spar (RS), side-of-body ribs, and upper and lower skin panel. A midspar (MS) runs from the wings through the WCS. In addition to the FS, RS, and MS, three beams span the WCS. Span wise beam 1 (SWB1) is located between RS and MS. Span wise beam 2 (SWB2) and span wise beam 3 (SWB3) are located between the MS and the FS. The center wing fuel tank (CWT) in incorporated into the WCS between RS and SWB3 with a dry bay between SWB3 and FS. The WCS measures approximately 21 x 22 x 5 feet in size.

C2. Static vs. dynamic failure

An issue in solving the inverse problem for TWA Flight 800 is whether the loading was dynamic or quasi-static. One question that arose was whether a simple static loading with equal pressure in all compartments would have caused the observed damage in the WCS. If there had been a static or a slow-rise-time loading, then solving the inverse problem will be impossible.

Determining the nature of the damage caused by the explosion in the WCS is very difficult, because of the multiple events that occurred during the crash and the breakup of the plane. Damage occurred in six different phases during the mishap sequence:

1. tank explosion,
2. tank decompression,

3. major structural breakup and fire,
4. water impact,
5. crush by water pressure at depth,
6. impact with ocean floor.

Additional, though lesser, potential for damage and masking of evidence occurred during the exposure of the wreckage to the salt water environment and in the recovery operations.

For many of the airframe pieces, the energy in the water impact proved much larger than the energy in the explosion. The excessive damage on many of the pieces from multiple high energy events makes it very difficult to tell which event caused the damage. More can be learned from the lack of damage, as the 'undeformed' parts often tell more of a story than the deformed parts. For example, if we find a fuel or vent tube from the center section that sustained crushing, then we cannot tell if the crush occurred from the explosion or from water pressure as the part sank. However, if we find a tube that is uncrushed, then we know that the pressure from the explosion did not exceed the crush strength of the tube.

Parts of SWB3, FS, keel beam, and the door on SWB2 were ejected from the aircraft before major structural breakup and before the water impact. The damage caused by water impact on these pieces was much less due to the slower falling velocity and relatively light mass.

C2.1. Simultaneous failure at multiple locations

Several factors led us to believe that the event was a dynamic loading and non-uniform within the tank. One such factor is simultaneous failure at multiple locations. A characteristic of dynamic loading is multiple simultaneous failure points. For example, if a grenade is loaded slowly, one crack will form and lead to a single split. If it is loaded dynamically, multiple cracks will form and fragments will result. The description below details the information that leads us to this hypothesis.

Based on the uniform fractures that we saw on SWB3, we believe that a detonation occurred. If a slow burn to a pressurization of 20+ psi occurred, then we would have expected a small localized failure to occur in the weakest area. This would lead to venting of the fuel cell and pressurization of the dry cell. Rapid flow between the two cells could have caused additional failures on SWB3, but we would expect to view twisting and non-uniform fractures. In addition, the front spar would fail in a similar fashion. We believe the evidence suggests a different damage scenario. The evidence suggests that SWB3 underwent uniform loading, fractured, and uniformly impacted the front spar. We believe that only a rapid pressure pulse (shock) could have caused this damage scenario.

The failure of SWB3 was uniform, with the upper chord fracture initiated at multiple locations and progressing essentially the full width of the beam. Most of the attachment points along the top of SWB3 failed in exactly the same way. Two different types of vertical stiffeners were used on SWB3. Those that were connected to upper seat bracing failed in shear, while those that were simply riveted to the top panel failed by tension pullout.

If the loading were static, one would expect one point to fail, with local deformation and twisting causing the surrounding areas to fail in a slightly different way. One would expect to see more of a decompression 'blow-out', i.e. start with a small hole that grows as the air pushes the hole larger. Further evidence of the uniform failure of SWB3 was the uniform impact of SWB3 into FS as it rotated forward into the front spar. Boeing estimated the strength of SWB3 at 16-21 psi.

In addition to the uniform failure of SWB3, the rivets along the bottom of SWB2 were pulled out in tension, then pushed back when the lower skin panel recontacted SWB2. It is possible that the rivets were pulled out after the explosion; however, the sequencing report indicated that these rivets separated from the lower skin panel before major fire exposure. Recontact damage pushed the rivets back through the holes. The recontact damage would be consistent with elastic rebound of the lower skin after a dynamic loading.

If the rivet failure in SWB2 occurred under a static loading, then the pressure load would be equal in all compartments. One would expect to see tensile rivet failures in the midspar and SWB1. An explosive loading that loads the lower panel and SWB3 at the same time would cause the failure of the rivets on SWB2 to occur at approximately the same time as failure of SWB3.

The manufacturing access door on SWB2 failed by a combination of shear and tension, with the shear failure occurring first. The shear failure is believed to be caused by relative vertical motion between the top and bottom skin panels.

C2.1.1. High pressures on front spar

The high speed impact of SWB3 into the FS and the pressure damage on the FS leads us to believe that the pressure behind SWB3 could have been much higher than the 20 psi needed to fail SWB3. The damage to the FS by SWB3 resulted in impact damage to the vertical stiffeners on the FS. The FS was deformed in a forward direction on both sides of the two water tanks which are mounted on the front face of the FS at the center. The mass of the tanks and the presence of the keel beam restricted deformation in the center of the FS. The mass and nature of the impact of SWB3 would not be enough to cause the deformation of the FS around the water tanks. Enough pressure had to be released into the dry bay to tear the FS along the top and push the FS around the water tanks. Note that the dry bay was vented with over 300 square inches which would rapidly bleed pressure to other parts of the structure. The nature of the damage, combined with the venting, leads us to believe that the pressure behind SWB3 was greater than 20 psi. A more detailed analysis could help us determine the pressure behind SWB3.

Two potable water tanks are located on the forward side of the front spar. The forward side of the right bottle contained impact marks and fracture that roughly corresponded to the cargo floor structure. Impact between the water tanks and the floor structure would require the tanks to accelerate and rotate forward. Accelerating the large mass of the full tanks would require high pressure acting on the front spar.

C2.1.2. Side-of-body ribs

The center wing section is separated from main wing tanks 2 and 3 by Side of Body Ribs. These ribs appear to be weak compared to SWB3. Under static loading, the fuel in the outer tanks would have had time to displace, leading to a possible failure between the wing tanks and WCS. In a dynamic event, the fuel in the wing tanks acts as an inertial boundary condition that causes the side-of-body ribs to see little strain.

C2.1.3. Top and bottom of tank

Under static loading, one would expect the top and bottom of the tank to deform uniformly from front to back. There was too much damage to the top and bottom of the tank from major plane breakup and water impact to determine if the tank deformed uniformly. However, since the keel beam failed in a manner that is consistent with displacement of the bottom of the tank deflecting non-uniformly downward, the damage to the keel beam could be used to locate the center of pressure. Current estimates have the over pressure acting approximately in equal amounts in the bays immediately ahead of and behind SWB2.

C2.1.4. Keel beam

Separation between the top of the keel beam and the bottom of the WCS is required to fail the bolted connection between these components. Loading to cause separation of the keel beam from the WCS could have come from either or both of two locations. The first location is under the front spar. As the front spar rotated forward, a prying action resulted at the front of the keel beam that could have caused the failure of the forwardmost set of bolts. In addition, there is a buckle in the web of the keel beam under SWB2 that is consistent with a localized vertical downward load on the top of the keel beam. This load could have resulted from a rapid downward movement of the bottom of the WCS at this location due to the overpressure event. Such movement of the bottom of the WCS is again indicative of a rapid pressurization which resulted in multiple near simultaneous failures.

C2.1.5. Honeycomb access doors

There are honeycomb access doors through SWB1, MS, and SWB2. Boeing estimated the strength of the honeycomb access doors at 20 psi. If analysis shows that the pressure behind SWB3 needed to cause the pressure damage in the FS was much greater than 20 psi, then we can establish a pressure gradient from the front of the WCS to the rear of the WCS.

The access doors give a good indication of the maximum pressure acting on the span wise beams and MS. They are composed of an aluminum honeycomb sandwich with an outer skin that will burn. Once the outer skin has burned, the doors are quite weak. The fact that the burned doors were intact, indicates that little or no water impact loading occurred to the doors. The doors are bolted along the sides, with no fasteners at the top and bottom. A metal edge strip along the top and bottom of the doors was used to reinforce the doors. Up to one-half inch of deformation occurred in the edge strip along the top and bottom of some of the doors. A static pressure test (using a rubber bladder) could be used to determine the pressure deflection characteristics of these doors. While we do not know if the doors were loaded by explosive compression or by decompression, pressure testing of the doors will give us upper and lower limits to the relative pressure on the doors.

The doors on SWB1 and the midspar were not blown out. SWB1 did show signs of aft pressure loading. Deformation on the left side door of SWB1 was greater than on the right side door. The left side midspar door was loaded forward, and the right side was loaded aft.

C2.1.6. Relative pressure on SWB2

The relative pressure on either side of SWB2 is unknown. The deformation of the yellow manufacturing access door on SWB2 clearly indicates that the door was blown forward. What is not clear is if this damage was caused by the explosive loading or by a rapid decompression. Note that there are similar doors on SWB3 that did not blow out. This leads us to believe that the blowout of the manufacturing access door on SWB2 was caused by it being damaged first in shear.

In addition to the manufacturing access door, SWB2 has a smaller sandwiched honeycomb access door that was blown forward. Since the honeycomb on the door was not intact, we do not know if the blowout was caused by water impact. There was fire damage on the remains of the blown door, which leads us to believe that the door was blown out by explosive compression or by decompression. If the blowout was caused by explosive compression, then there was more pressure on the backside of SWB2 than on the front of SWB2. If this were the case, then one would expect the other doors on the midspar to be damaged. If the blowout was caused by decompression, then there would have to be pressure to the rear of SWB2, which would be consistent with a burn that proceeds from the back to the front of the WCS.

C2.1.7. Vent and fuel tubes

The vent and fuel tubes in the WCS indicate that some of the bays may have had very little overpressure. At least one tube from the WCS was found that was not crushed. (Tube crush strength was estimated by Jim Wildey at 8 psi. Tests to determine the crush strength of the tube need to be performed. We also need to know where the tube could have been located. If it was in the front of the tank, then we would certainly have some BIG questions).

C2.2. Pressure gradient

We believe that a pressure gradient existed from the front of the CWT to the back. A detailed structural analysis is needed to establish if a pressure gradient would result in the damage observed. Once the pressure gradient from front to back of the CWT has been established, testing combined with combustion analysis can be used to determine if it is possible to generate such a pressure given the distribution of the flammable mixture in the tank.

The CWT failure was very symmetric, with no evidence of a pressure gradient in the front bays. There was some evidence (access doors) that a slight pressure gradient may have existed in the aft bays.

There was no evidence that a strong pressure gradient existed between the top and bottom of the CWT.

C3. Preliminary conclusions

As a result of inspecting the reconstructed airframe, SNL is confident that there is sufficient forensic information to justify continuing with modeling the airframe. The results, to date, of the inspection are:

- *There is information from the explosion and decompression that can be separated from the breakup and water impact. Therefore, it is useful it continue to develop analysis models of the structure to correlate with the reconstructed airframe.*
- *The observed deformation is not consistent with a static pressure buildup; thus it is not impossible to solve the inverse problem associated with reconstructing the dynamic event that led to the accident.*

Appendix D: Proposed Joint Testing Program with Caltech: Large-Scale Testing of Fuel Tank Explosions

proposed by

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[redacted] (b)(6)

Summary

It has been recognized that the combustion of JP-A fuel inside the center fuel tank may have been responsible for the demise of TWA Flight 800. Although evidence to date is unclear and somewhat speculative, this possibility cannot be ruled out. The National Transportation Safety Board (NTSB) is proposing to sponsor a series of large-scale combustion tests in an effort to help determine the likelihood of a such an explosion. Caltech University has been given the lead for these tests and is looking for facilities capable of conducting such tests. Over the past two decades, Sandia National Laboratories has conducted research on both gas- and liquid-phase combustion and has existing facilities capable of conducting such a testing program. This proposal outlines Sandia's preliminary proposal to participate in these tests with Caltech University.

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Introduction

The wreckage from the crash of TWA Flight 800 has been reviewed and inspected by several world-renowned experts with mixed conclusions. One possible reason for this crash is inadvertent combustion or detonation of JP-A fuel remaining in the center fuel tank. The center fuel tank is a rigid, roughly rectangular aluminum cell. The fuel tank is divided into several compartments by floor-to-ceiling partitions which run from one side of the tank to the other. These partitions are constructed of vertical aluminum I-beams about one-foot apart and covered on one side with a thin aluminum sheet. There are fuel pass-through holes about three to four inches in diameter along the bottom of the partitions and one to two inches off the floor of the fuel tank. It has been estimated that 50 to 100 gallons of JP-A fuel were present in the center fuel tank when the flight left New York's John F. Kennedy airport.

Conditions that lead to combustion and possible transition to detonation of JP-A fuel is of interest in helping to resolve the cause of this tragedy. Currently available data do not provide the information required to accurately determine the conditions required for combustion and/or detonation. To assist in this resolution, the NTSB is sponsoring a series of large-scale tests using ¼-scale replicas of the center fuel tank.[10] Sandia National Laboratories has conducted research on both gas- and liquid-phase combustion of hydrocarbon fuels and has existing facilities capable of conducting such a testing program. This proposal outlines Sandia's preliminary proposal to participate in these tests with Caltech University.

Proposed testing program

Joe Shepherd and Merritt Birky have outlined the preliminary testing program in Reference 10. Since that letter, additional conversations with Joe Shepherd have led to the following understanding of the testing program:

1. Approximately 25 tests will be conducted in ¼-scale fuel tanks (referred to hereafter as the test article) which have a footprint of 5 ft x 5 ft and are 1 ½-feet tall.

2. The fuel will not be JP-A, but will likely be propane, hexane, octane or another of the pure alkanes with a slightly higher vapor pressure to simulate a reduced atmospheric pressure. Approximately 50 gallons (5 kg) of fuel will be used in each test and will be spark ignited.

3. The test article will be placed on the ground and instrumented with thermocouples (≤20), pressure gauges (≤20), photosensors (≤20), and motion sensors (≤20). Each test will be recorded with high-speed photography and standard VHS.

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10 "Large-Scale Testing of Fuel Tank Explosions," Letter from J. E. Shepherd (Caltech) and M. M. Birky (NTSB), March 18, 1997.

From the preliminary test description,[10] it is assumed that the test articles (i.e., scaled fuel tanks) required for this testing program will be provided by either NTSB or Caltech. Furthermore, from conversations with Joe Shepherd, it is likely that some of the instrumentation will be provided by Sandia and others by Caltech. Depending upon how this is finally resolved and how the responsibility for instrumentation and the test articles is assigned, Sandia reserves the right to revisit the cost estimate presented in the next section.

Given these requirements and conditions, Sandia National Laboratories proposes to provide the following:

1. The Explosive Firing Site (shown in Figure D1) has been used over the past two decades to conduct gas- and liquid-phase combustion testing, as well as conventional explosive testing. The tests will be conducted at one of our explosive testing pads which has ample room to conduct such tests. Personnel will be provided to work on these tests, including persons responsible for data acquisition, instrumentation and wiring, mechanical design and fabrication, and general site safety. Additionally, personnel will be provided to prepare the safe operating procedures and environmental permits/documents required to perform these tests.

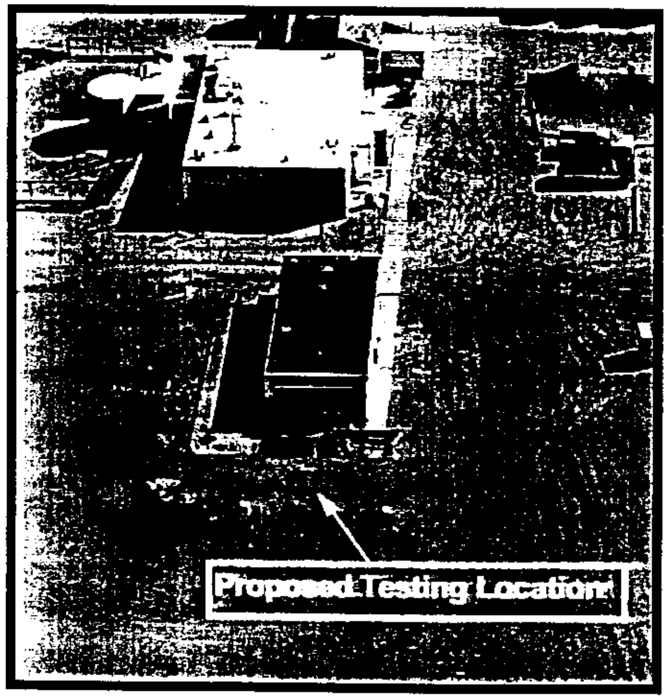

Figure D1 Proposed Testing Location at the Explosive Firing Site.

2. Up to 75 channels of data acquisition capability will be provided by Sandia and will include 50 channels which can be digitized at rates of at least 1 kHz and 25 channels which can be digitized at rates of at least 250 kHz. Sandia will provide personnel who are capable of configuring, troubleshooting, and extracting data from the computer-based data system.
3. High-speed photographic coverage of each test will include up to two each, 16-mm cameras operating at 500-1000 fps and two each standard VHS (i.e., 30 fps) cameras. Personnel will be provided by Sandia to set up, operate, and develop films for all tests.

4. The following is a preliminary list of equipment and instrumentation to be provided by Sandia as a part of this proposal:
    4.1. Thermocouple extension wiring for up to 40 Type K thermocouples,
    4.2. BNC lines for up to 25 pressure gauges,
    4.3. Charge amplifiers for up to 15 PCB pressure transducers,
    4.4. Differential amplifiers for up to 15 Kulite pressure transducers,
    4.5. Twisted pair wiring for up to 15 photodiodes,
    4.6. Twisted pair wiring for up to 15 strain gauge or motion detectors, and
    4.7. High voltage fireset and cabling capability to spark-initiate the gaseous mixture.
5. In addition, Sandia offers on-site welding and metal working capabilities. The Explosive Firing Site has an active machine shop with qualified personnel to make hardware for such field-testing activities. If detailed parts are required, Sandia has machine shop capabilities and there are machine shops locally in Albuquerque, New Mexico.
6. Qualified personnel experienced in the set up and conduct of explosive tests in a remote setting will be provided The following capabilities will be available if this work is supported at Sandia:
    6.1. <u>Experienced Explosive Project Manager:</u> Advanced degree in engineering with more than 14 years experience in setting up and executing tests related to conventional explosives, gas-phase combustion, gas-phase detonations and fuel-air explosives.
    6.2. <u>Experienced Field Test Engineer:</u> Advanced degree in engineering with more than 25 years experience in the setting up and execution of explosive and explosive-related tests at Sandia's remote sites and at the Nevada Test Site.
    6.3. <u>Experienced Combustion Engineer:</u> Advanced degree in engineering with more than 15 years experience in combustion-related phenomena.
    6.4. <u>Experienced Data Acquisition Technicians:</u> More than 10 years of experience at Sandia performing tests at remote sites using slow- and high-speed data acquisition systems including CAMAC crates, HP systems, and IBM-based systems.
    6.5. <u>Experienced Mechanical Technicians:</u> More than 10 years of experience at Sandia performing tests at remote sites designing, building and instrumenting test apparatus for use in explosive tests and other types of testing requiring remote control.

Preliminary schedule and cost

In the following two tables, preliminary estimates of the schedule and cost to conduct the proposed work are shown. The project will begin with a kick-off meeting at Sandia with all personnel involved (both from Sandia and Caltech). This will provide an opportunity to ensure that everyone understands the requirements and schedule of the project and to assign responsibility for each element of the project. At this writing, the proposed tests will be conducted on the explosive pad located just west of Building 9920 at Sandia Explosive Firing Site (refer to Figure D1). This location is rated for up to 50 lbs of explosives (or equivalent) and has been used in the past for similar types of testing.

As shown below in the preliminary schedule, the first one and a half months of this program will be spent working two parallel efforts: (1) preparation of the data acquisition system including wiring, hardware and software setup and checkout, etc., and (2) preparation and approval of the required site-safety and environmental documentation necessary to perform these tests (i.e., safe operating procedure, air burn permits, etc.). Once this has been completed, it is projected that testing will begin two months after the start of the program. During the next five and a half months, tests will be conducted at a frequency of about two per week. This is a preliminary estimate as the details of instrumentation and how each test will be set up are still uncertain. At the close of this testing program (up to 25 tests conducted in total), a complete set of digital data will be provided to Caltech. Sandia will also work with personnel from Caltech and the NTSB to better understand and interpret the data.

Preliminary Schedule

Description	Month from Kick-off
Project kick-off[11]	0
Run instrumentation wiring and set up of data acquisition system	1.5
Prepare ES&H approval to perform tests	1.5
Run 1st ¼-scale fuel tank test	2
Run ≤ 25 tests in ¼-scale fuel tanks - (2 per week)	≤ 5.5
Provide complete data set to Caltech. Help prepare report.	6.5

The costs associated with the conduct of these tests are preliminary and based on incomplete information concerning the tests. Sandia reserves the right to reconsider these estimates during the selection process and during final negotiations for the project. If costs change, they will be clearly spelled out to Caltech and the NTSB. Given these

[11] Project kick-off assumes that Sandia has funding in-hand and there is an internal case number available for charging. The time required to process the funding from NTSB through DOE to Sandia is not considered as part of this time estimate.

conditions, the preliminary costs associated with conducting these tests is estimated to be $450K (a detailed breakdown of costs is available if required).